

FOST 2 upgrade with hollow-fiber CTA FO module and generation of osmotic agent for microorganism growth studies

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FOST 2 is an integrated membrane system that incorporates a forward osmosis subsystem and a reverse osmosis subsystem working in series. It has been designed as a post treatment system to process the effluent from the Membrane Aerated Biological Reactor developed at NASA Johnson Space Center and Texas Tech University. Its function is to remove dissolved solids residual such as ammonia and suspended solids, as well as to provide a physical barrier to microbial and viral contamination. A tubular CTA membrane module from HTI and a flat-sheet lipid-base membrane module from Porifera were integrated and tested on FOST 2 in the past, using both a bioreactor's effluent and greywater as the feed solution. This paper documents the performance of FOST 2 after its upgrade with a hollow-fiber CTA membrane module from Toyobo, treating real black-water to generate the osmotic agent solution necessary to conduct growth studies of genetically engineered microorganism for the Synthetic Biological Membrane project.

Nomenclature

ARC	=	Ames Research Center
CTA	=	cellulose triacetate
DI	=	deionized
FO	=	forward osmosis
FOST	=	forward osmosis secondary treatment
JSC	=	Johnson Space Center
ldl	=	lower than detectable limit
MABR	=	Membrane Biological Reactor
NaCl	=	sodium chloride
NASA	=	National Aeronautics and Space Administration
OA	=	osmotic agent
RO	=	reverse osmosis
SBS	=	sodium bisulfite
TDS	=	total dissolved solids
TOC	=	total organic carbon

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I. Introduction

THE Forward Osmosis Secondary Treatment 2 (FOST 2) system is designed to treat spacecraft wastewater. Originally it was designed as a post treatment system to process the effluent from the Membrane Aerated Biological Reactor (MABR) under development at NASA Johnson Space Center (JSC) and Texas Tech University. Its function is to remove residual dissolved solids, ammonia, suspended solids, and to provide a physical barrier to microbial and viral contamination. However, FOST 2 has also proven to be a very expandable platform for testing new membranes with the most diverse feed solutions. In fact, besides treating the bioreactor's effluent, FOST 2 has been tested using greywater collected from the Sustainability Base Building at NASA Ames Research Center (ARC) as the feed solution in order to investigate its capability to be potentially used as a primary treatment system. FOST 2 has also been tested using a black-water ersatz to prove its capability to process wastewaters with high concentrations of organic material. Initially, an ersatz solution based on miso has been adopted as the feed on FOST 2. However, the low solubility and property to bond in macroscopic particles of its components led to the plugging of the FO module. For this reason, a review of other existing simulants for fecal sludge has been performed and has identified a composition of kaolin, bentonite, topsoil, compost, maize meal and wheat flour as an alternative black-water simulant material. As part of the Synthetic Biological Membrane project, FOST 2 is used to generate real osmotic agent (OA) solution that is necessary for growth studies of the genetically engineered microorganism that will hyper-express fatty acids and fatty alcohols involved in membrane regeneration.

II. Background

Forward osmosis (FO) is a physical phenomenon that allows the transport of water across a selectively permeable membrane from a region of higher water chemical potential to a region of lower water chemical potential. It is driven by a difference in solute concentrations across the membrane itself, which causes a difference in osmotic pressure that allows passage of water but rejects most solute molecules.

Reverse osmosis (RO) uses hydraulic pressure to oppose, and exceed, the osmotic pressure of an aqueous feed solution to produce treated water. Thus, in reverse osmosis, the applied hydraulic pressure is the driving force for mass transport through the membrane. In forward osmosis, the osmotic pressure itself is the driving force for mass transport.

The main advantages of using FO are that it operates at low or no hydraulic pressures, it has high rejection of a wide range of contaminants, and it has a lower membrane fouling propensity compared to pressure-driven membrane processes. The source of the driving force in the FO process is the concentrated solution on the permeate side of the membrane. We used a sodium chloride (NaCl) solution as the osmotic agent (OA) because of its high solubility and the simplicity to be concentrated to achieve very high osmotic pressures

NASA has been investing on the development of FO technology for recycling water on future long duration human space missions since the '90s. A microgravity flight experiment was completed in 2011 on board the Space Shuttle Atlantis and demonstrated that the FO process works in microgravity but at reduced flux rates. A green building that integrates a greywater reclamation system similar to FOST 2 has been built at NASA Ames Research Center, showed in Figure 1. This system, which is much bigger than FOST 2, reclaims wastewater from sinks and showers and uses it as toilet flush water. The objective of this installation is to demonstrate continuous, long-term operations of the system and to determine operating costs, membrane life, and other parameters that will need to be considered when designing a wastewater reclamation system for a planetary base.

Figure 1. Sustainability Base at NASA ARC.

Greywater is, by definition, all wastewater generated in households or office buildings from streams without fecal contamination. Sources of greywater include sinks, showers, baths, clothes washing machines or dish washers. However, under certain conditions traces of feces, and therefore pathogens, might enter the greywater stream via effluent from the shower or washing machine. Streams of wastewater from toilets, containing feces, urine, and flush water are defined black-water.

III. Materials and Methods

FOST 2 is based on a continuous flow process that is achieved by extracting the water across the FO membrane into the osmotic agent solution and then treating the latter in the reverse osmosis subsystem. This continuous flow process is shown in Figure 2.

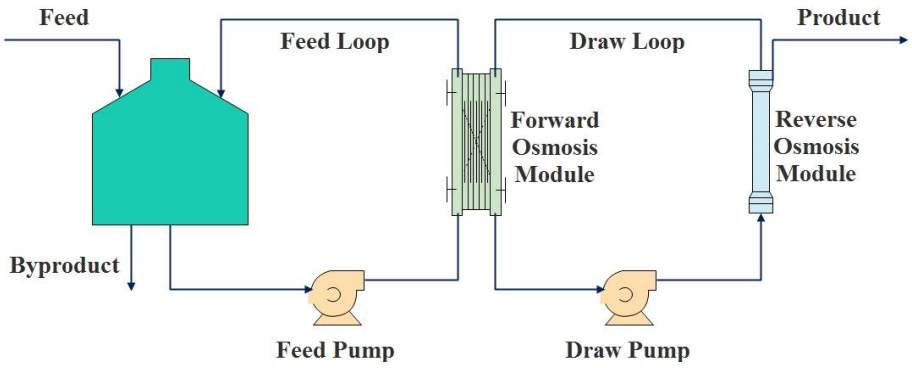

Figure 2. Simplified FOST2 flow diagram.

The FO subsystem is composed of a HPC3205 module (9 cm in diameter and 83 cm long) from Toyobo, showed in Figure 3. The membrane surface area is 31 m^2 and it is in a hollow fiber configuration. The number of hollow fibers is 99,000 with an outer diameter of 175 µm and an inner diameter of 85 µm. The membrane is constructed in cellulose triacetate (CTA) and is stable between pH 3 and 8. The operating pressure cannot exceed 5 bar on the shell side and 1 bar inside the hollow fiber. The membrane has a salt rejection between 96 % and 98 % when tested at 15 bar in an RO mode with a 1500 ppm NaCl solution.

The RO subsystem is composed of an 80E module from Katadyne, and it uses an energy recovery pump. The RO membrane has salt rejection rates ranging from 98.4% to 99%. The RO membrane module ensures pure product water but requires extremely high pressures.

Pressure relief valves (set at 10 PSI for the FO loop and 1000 PSI for the RO loop) are used to protect the FO membranes from being over pressurized as well as a safety precaution in the RO high-pressure loop. Two digital scales measure the mass of the feed and of the product tanks. The system is operated until the desired water recovery rate is achieved. An anti-scalant solution is added to the feed tank before the system is started. When the run is completed the system is flushed with deionized (DI) water and then a sodium bisulfate (SBS) solution is recirculated through both the loops to preserve the membranes between wo consecutive runs.

The feed used for the Synthetic Biological Membrane project is human urine and has been collected during several days from different collecting stations. Donors were both males and females. In order to minimize degradation, the feed, once collected, was stored in a refrigerator and its pH was adjusted to 5. The initial feed volume processed by the system is 60 L and is driven by the desired water recovery rate and the dead volume of the feed loop. The feed is recirculated through the shell side of the FO membranes through a pump by first passing across a 20 µm filter and then through the HPC3205 element before returning to the feed tank. The FO pump is a variable speed pump. The objective of this test, run in triplicate, is the generation of real osmotic agent solution that is used for growth studies of genetically engineered microorganism. The targeted water recovery rate is 87 %.

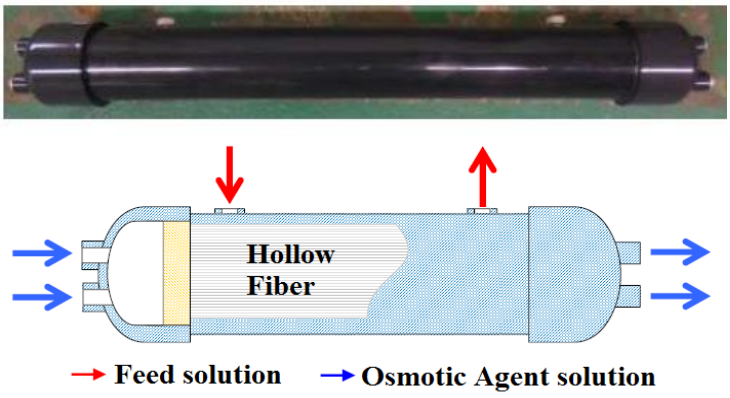

Figure 3. HPC3205 FO module from Toyobo.

At the beginning of the first run, the OA tank contains 10 L of 10 g/L of NaCl solution and is recirculated through the support side of the FO membrane via the RO subsystem. Here, the FO subsystem is coupled with the RO subsystem. The concentrated OA solution drives water across the FO membranes. Clean water is then removed from the OA through the RO membrane module into the product tank. The second and the third runs have been accomplished reusing the OA from the previous run, which has been stored in the refrigerator between the runs. The initial volumes of the second and of the third runs were lower than 10 L because of samples collection and because of other minor losses.

IV. Results

This section details the results of the three runs obtained from the testing of the FOST 2 system using the Toyobo FO element and treating human urine as the feed solution.

Figure 4 shows a graph of the volumes of the feed, the product, and the OA solutions during the first run. The water recovery rate achieved at the end of the run is 86.8 %. The overall mass of NaCl used considering both the salt present initially in the OA and the salt added during the run, is 475 g. The initial error on the OA volume curve indicates that the initial osmotic potential of the OA was too low and thus less water is extracted from the feed to the OA across the FO module than the amount of product water extracted across the RO module. After a certain amount of time an equilibrium is reached and the level remains constant until the osmotic pressure differential drops below this equilibrium. To restore the equilibrium status, NaCl is added into the OA tank. When approaching the end of the run, and thus at higher feed and OA concentrations, the osmotic pressures in both the subsystems rise, reducing the production rates and thus the flow rates.

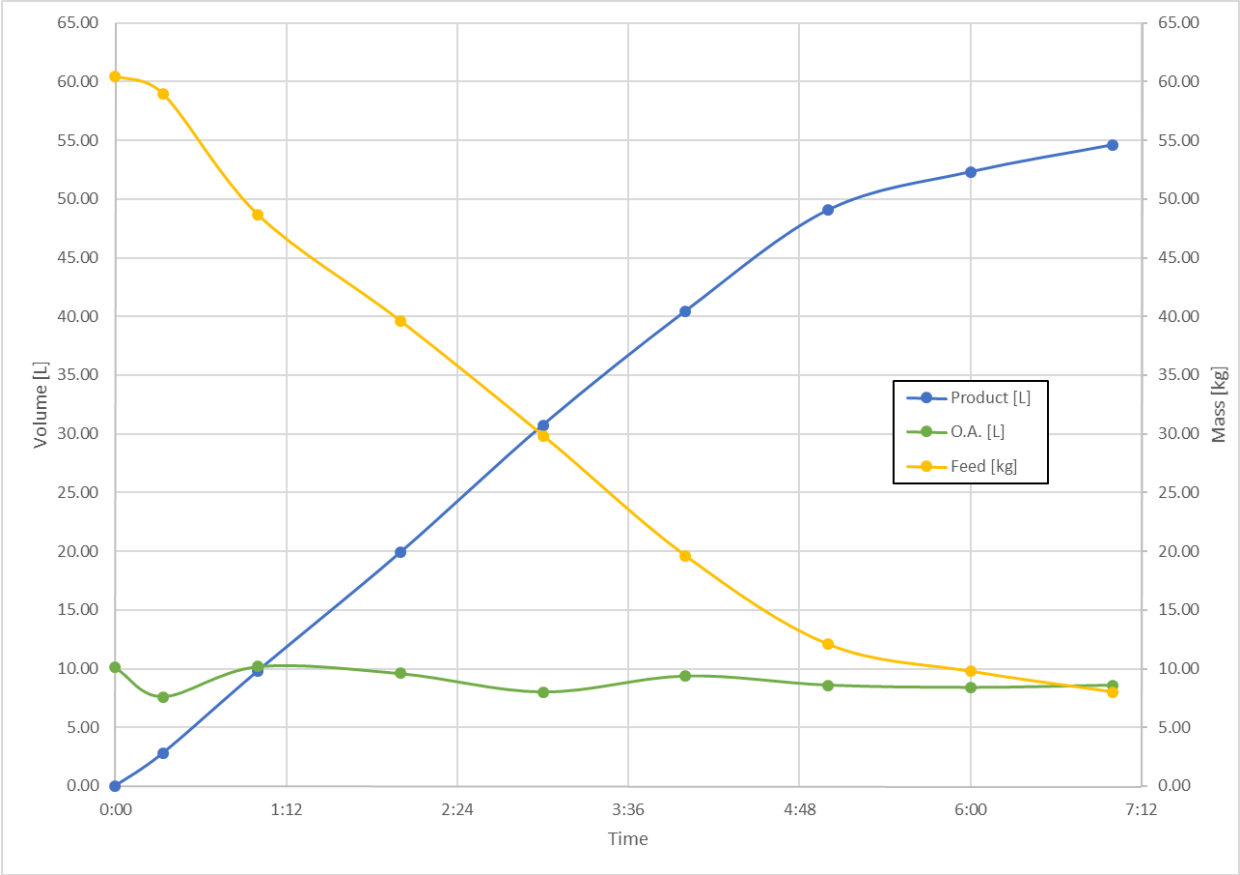

Figure 4. Flow rates during the first run.

Time	Feed [kg]	Product [kg]	O.A. [L]	Salt replenish [g]	RO pressure [psi]	FO feed in [psi]	FO flow rate [GPH]
0:00	60.44	0	10.1	100	0	0	0
0:20	58.94	2.8	7.6	100	800	2	23
1:00	48.64	9.8	10.2	-	900	3	23
2:00	39.6	19.9	9.6	-	950	3.25	23
3:00	29.84	30.75	8	100	950	3.5	23
4:00	19.6	40.45	9.4	75	950	4	25
5:00	12.06	49.05	8.6	75	950	4	25
6:00	9.76	52.3	8.4	25	900	4	25
7:00	8	54.6	8.6	-	950	4	25

Table 1. Operational data of the first run.

The volume of the OA solution at the end of the run is lower than that at the beginning of the run because of the dead volume within the OA loop and because the amount of product water extracted across the RO module was higher than the volume of feed treated. After the run, salt leaking tests have been successfully conducted to verify the integrity of the membranes. Table 1 summarizes the operational data collected during the first run.

The results of the chemical analysis performed on samples collected from the feed, OA, and product tanks initially and at the end of the run are shown in Table 2. The concentration of NaCl in the feed increases more than the concentration of the other anions and cations because of the permeation of salt across the FO membrane from the OA. Total organic carbon (TOC) values in the OA are > 5000

Figure 5. Samples (from the left: feed, OA, product).

Sample I.D.	Na	NH4	K	Mg	Ca	Cl	NO2	Br	NO3	PO4	SO4	TOC	%TDS Filtered
Feed initial	1365	338	1718	86	109	3387	Idl	Idl	Idl	2801	828	4012	1.77
Osmotic agent final	16660	Idl	Idl	Idl	Idl	27503	Idl	Idl	Idl	Idl	Idl	5354	5.04
Product final	57	<0.5	<0.5	<0.5	<0.5	116	<0.5	<0.5	<0.5	<0.5	<0.5	182	<0.5
Feed final	7323	2434	8269	474	541	14435	Idl	Idl	Idl	10099	4283	15090	7.33

Table 2. Chemical analysis of the first run.

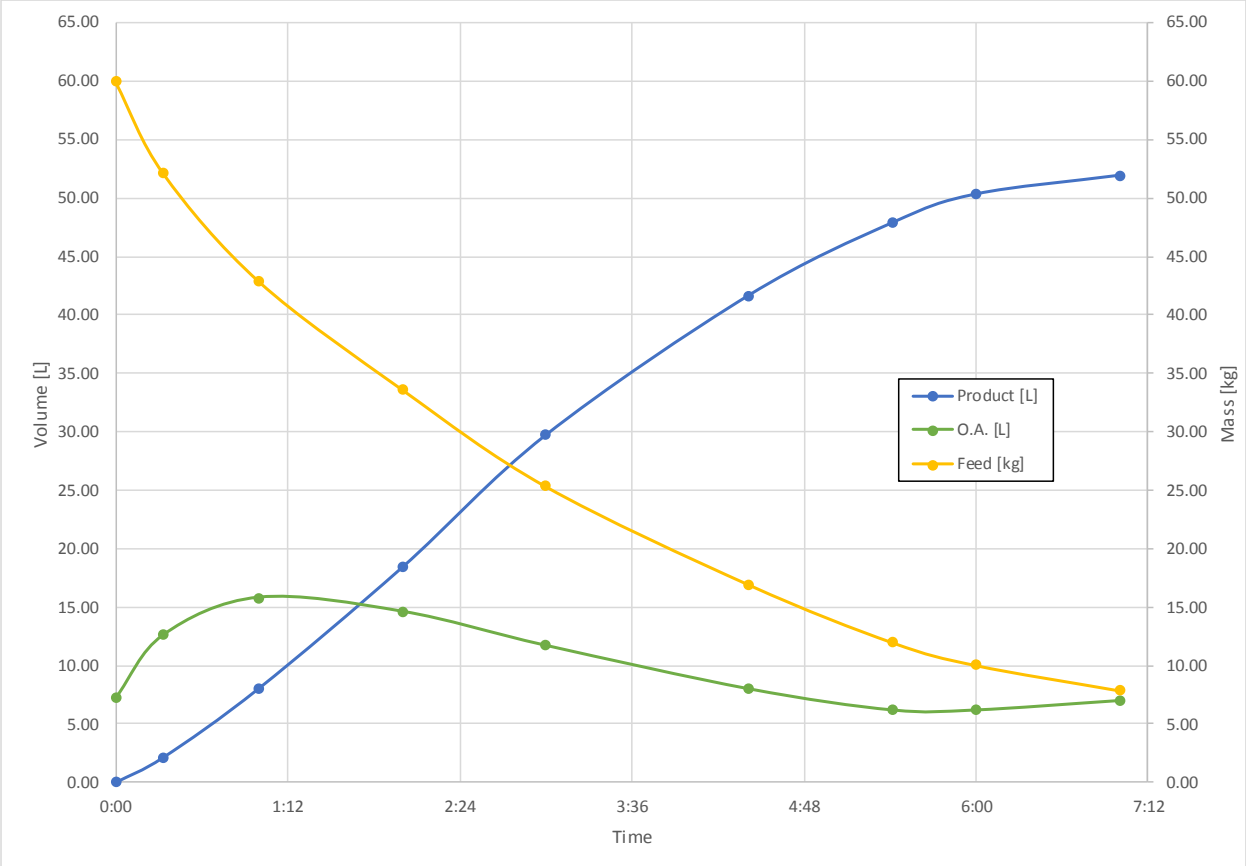

Figure 6. Flow rates during the second run.

ppm, higher than the TOC values of the feed at the beginning of the run. All the other ions besides sodium and chloride in the OA are below the detectable limit of the instrument. Total dissolved solids (TDS) were initially measured using the electro-conductivity method. However, since NaCl is not the only solute of the OA, the conductivity method provides only an approximate value for the TDS concentration. The analysis of the TDS using the more accurate gravimetric method has then been accomplished. The results obtained with the gravimetric method indicate an average TSD of the OA of 5.0 %. The average TDS of the feed at the end of the run is 7.3 %.

The final feed is very concentrated since 87 % of the water has been removed, as shown in Figure 5. The OA solution, which is clear at the beginning of the run, appears yellowish at the end of the run (middle vial in Figure 5). The product water appears perfectly clear at the end of the first run, although it has a slight smell of urine. This is explained by the presence, even if low, of uric acid and by the extreme sensibility of the human smell to it.

Time	Feed [kg]	Product [kg]	O.A. [L]	Salt replenish [g]	RO pressure [psi]	FO feed in [psi]	FO flow rate [GPH]
0:00	60	0	7.2	-	0	0	0
0:20	52.14	2.15	12.6	-	925	4	24
1:00	42.9	8.05	15.8	-	900	5	24
2:00	33.64	18.4	14.6	-	925	5	24
3:00	25.36	29.7	11.7	-	950	5	25
4:00	16.94	41.65	8	25	980	5	25
5:00	12	47.85	6.2	25	1000	6	25
6:00	10.04	50.3	6.2	60	975	5	25
7:00	7.88	51.9	7		975	6	25

Table 3. Operational data of the second run.

Figure 6 shows a graph of the volumes of the feed, the product, and the OA solutions during the second run. The water recovery rate achieved at the end of the run is 86.9 %. The overall mass of NaCl added to the OA, mostly at the end of the run, is 110 g. The initial trend of the OA volume curve indicates that the initial osmotic potential of the OA is very high because of the concentration achieved at the end of the first run, and thus much more water is extracted from the feed to the OA across the FO module than the amount of product water extracted across the RO module. After four hours of run and more than 70 % or feed processed, the osmotic potential of the OA needs to be adjusted in order to maintain its level constant. Table 3 shows the operational data collected during the second run. The results of the chemical analysis performed on samples collected from the feed, the OA, and the product tanks at the beginning, at the end, and every two hours during the second run are summarized in Table 4. The addition of further NaCl during the second run is due to the initial higher osmotic pressure of the urine compared to the first run. In fact, the concentration of NaCl in the feed at the beginning of the first run is almost double of what it was in the initial feed during the first run, as showed in Table 4. In order to maintain the same osmotic pressure differential between the OA and the feed, the concentration of NaCl in the OA at the end of the second run must be higher than it was at the end of first run. The concentration of NaCl in the final product is also higher compared to the previous run, but the difference is almost negligible and is due to the much higher concentration of the OA. The TOC values of the feed used in the second run are also almost twice as high as they were in the first run. The TOC in the OA at the end of the second run increased by 78 %. It represents the 44 % of the TOC in the final concentrated feed, while it was 35 % of the final concentrated feed during the first run. All the ions other than sodium and chloride in the OA are below the detectable limit of the instrument. The analysis of the TDS using the gravimetric method indicate an

Sample I.D.	Na	NH4	K	Mg	Ca	Cl	NO2	Br	NO3	PO4	SO4	TOC	%TDS Filtered
Feed initial	2796	1097	3491	Idl	Idl	6365	Idl	Idl	Idl	4930	1390	7471	3.10
Feed 2:00	3189	1209	3965	Idl	Idl	7369	Idl	Idl	Idl	5737	1544	8013	3.32
OA 2:00	8745	Idl	Idl	Idl	Idl	13960	Idl	Idl	Idl	Idl	Idl	3760	2.59
Product 2:00	30	<0.5	<0.5	<0.5	<0.5	63	<0.5	<0.5	<0.5	<0.5	<0.5	129	<0.5
Feed 4:00	5933	2052	7039	Idl	Idl	12565	Idl	Idl	Idl	10319	2963	15199	6.22
Osmotic agent 4:00	12894	Idl	Idl	Idl	Idl	22533	Idl	Idl	Idl	Idl	Idl	6628	4.18
Product 4:00	65	<0.5	<0.5	<0.5	<0.5	138	<0.5	<0.5	<0.5	<0.5	<0.5	252	<0.5
Feed final	12344	4151	12168	Idl	Idl	24542	Idl	Idl	Idl	17430	4773	21765	10.11
Osmotic agent final	19822	<0.5	<0.5	<0.5	<0.5	38940	Idl	Idl	Idl	Idl	Idl	9553	6.94
Product final	68	<0.5	<0.5	<0.5	<0.5	151	<0.5	<0.5	<0.5	<0.5	<0.5	268	<0.5

Table 4. Chemical analysis of the second run.

average TSD of the final OA of 6.9 %. The average TDS of the feed at the end of the run is 10.1 %. The product water appears perfectly clear at the end of the second run.

Figure 7 shows a graph of the volumes of the feed, the product, and the OA solutions during the third run. The volume of the OA solution at the beginning of the third run is lower than that at the beginning of the previous runs because of the dead volume lost within the OA loop when draining the system and because of the samples collected during the runs themselves. The water recovery rate achieved at the end of the third run is 87.0 %. The overall mass of NaCl added to the OA is 100 g. Similarly to the second run, the trend of the OA volume curve indicates that the initial osmotic potential of the OA is very high because of the concentration achieved at the end of the previous run. After five hours and 70 % or feed processed, the osmotic potential of the OA needs to be adjusted in order to maintain its level constant. Table 5 shows the operational data collected during the third run. The results of the chemical analysis performed on samples collected from the feed, the OA, and the product tanks at the beginning, at the end, and every two hours during the third run are summarized in Table 6.

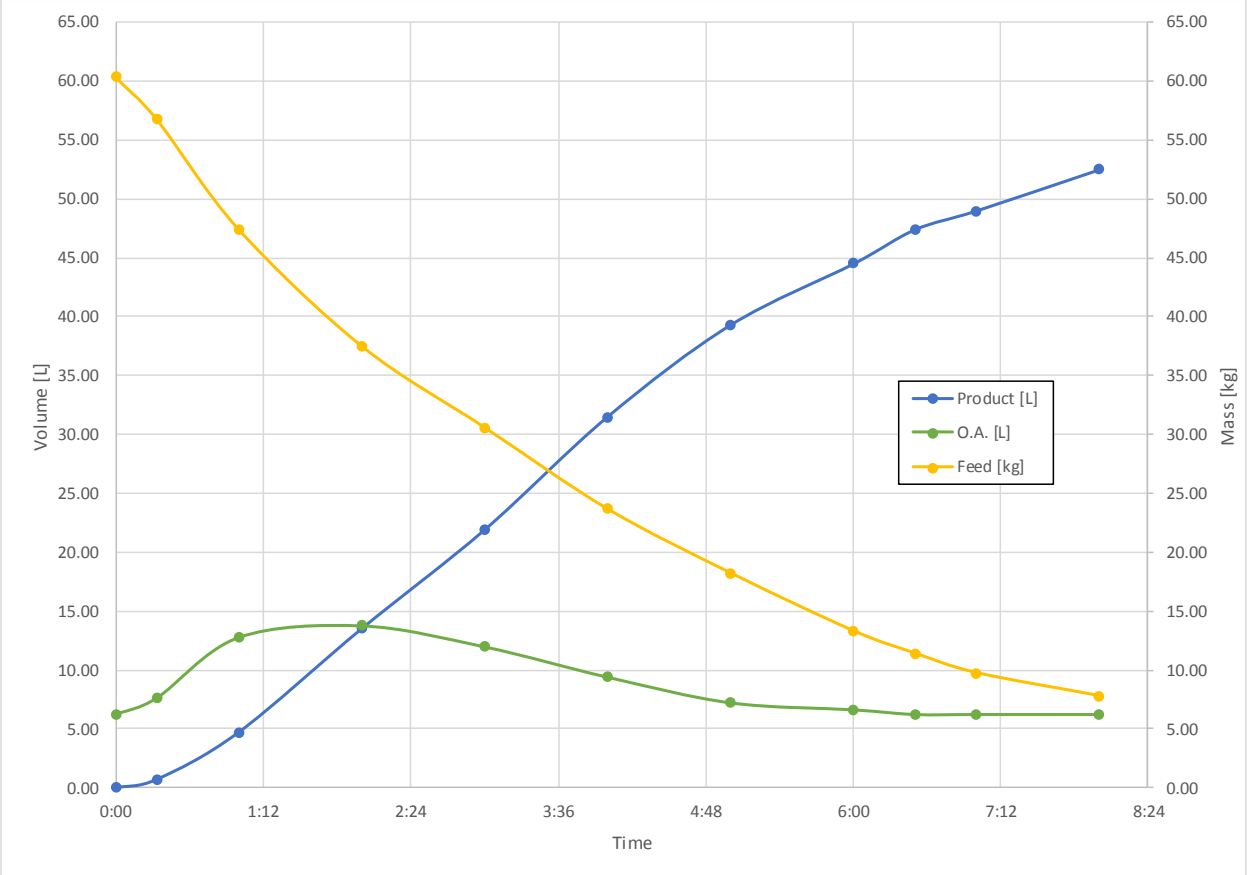

Figure 7. Flow rates during the third run.

Time	Feed [kg]	Product [kg]	O.A. [L]	Salt replenish [g]	RO pressure [psi]	FO feed in [psi]	FO flow rate [GPH]
0:00	60.34	0.00	6.2	-	0	0	0
0:20	56.78	0.70	7.6	-	950	5	25
1:00	47.42	4.70	12.8	-	875	4.5	25
2:00	37.50	13.50	13.8	-	875	5	25
3:00	30.58	21.90	12	-	875	5	25
4:00	23.66	31.50	9.4	-	900	4.5	25
5:00	18.22	39.30	7.2	50	925	4.5	24
6:00	13.30	44.50	6.6	50	900	4	24
6:30	11.40	47.40	6.2	0	925	4	25
7:00	9.74	49.00	6.2	0	950	5	25
8:00	7.78	52.50	6.2	0	950	5	25

Table 5. Operational data of the third run.

Sample I.D.	Na	NH4	K	Mg	Ca	Cl	NO2	Br	NO3	PO4	SO4	TOC	%TDS Filtered
Feed initial	1392	599.3	1599	72.53	93.83	3246	Idl	Idl	50.2	2442	807.7	3353	1.62
Feed 2:00	2122	834	2242	109.7	141.3	4624	Idl	Idl	Idl	3416	1022	4706	2.36
OA 2:00	5673	Idl	652.3	Idl	Idl	11661	Idl	Idl	Idl	Idl	Idl	3179	2.31
Product 2:00	32.43	5.33	3.05	<0.5	<0.5	64.33	<0.5	<0.5	0.9	1.6	1.6	161	<0.5
Feed 4:00	3521	1169	3169	157.7	201	7250	Idl	Idl	Idl	5060	1561	7180	3.42
Osmotic agent 4:00	7159	1066	1445	Idl	Idl	15063	Idl	Idl	Idl	822.7	373	5351	3.21
Product 4:00	26.53	4.56	3.36	<0.5	<0.5	53.4	<0.5	<0.5	0.96	1.667	1.06	163.3	<0.5
Feed final	11305	2385	6733	409	501.3	24321	Idl	Idl	Idl	14399	3565	15203	8.49
Osmotic agent final	13210	2109	4171	Idl	Idl	32304	Idl	Idl	307.5	3442	1222	9717	6.57
Product final	43.4	9.8	13.23	<0.5	<0.5	103.7	<0.5	<0.5	0.86	5.26	2.13	386.7	<0.5

Table 6. Chemical analysis of the third run.

The addition of further NaCl during the third run, even if lower than during the second run, combined to a lower concentration of NaCl in the initial feed, indicates a loss of salt across the two membrane modules. From the results of the chemical analysis it is calculated that of the 100 g of NaCl added to the OA, 59.4 g have crossed the FO membrane into the feed and 7.7 g have crossed the RO membrane into the product. This indicates that only around 33% of the NaCl added to the OA during the run serves to maintain the needed osmotic pressure differential between the OA and the feed. However, the concentration of NaCl in both the final OA and the final product is lower compared to the previous run. The TOC values of the feed used in the third run are much lower compared to the previous runs. The TOC in the OA at the end of the third run, instead, increased by 1.7 % with respect to its initial value. This increase is almost negligible compared to the increase achieved at the end of the second run. It represents the 64 % of the TOC in the final concentrated feed. Some ions other than sodium and chloride in the OA are present at negligible levels. The analysis of the TDS using the gravimetric method indicate an average TSD of the final OA of 6.6 %, similar to the previous runs. The average TDS of the feed at the end of the run is 8.5 %. The product water appears perfectly clear at the end of the third run.

V. Conclusion

The FOST 2 system has successfully processed human urine feed into a product solution meeting the required water recovery rate of 87 %. A consistent amount of NaCl added to the OA has been lost across the FO membrane into the feed. Implementation of a better pressure control should prevent this from happening in future runs. Little difference in the final values of TOC and TDS in the OA has been achieved between the second and the third run. The chemical analysis shows the presence in the OA of components other than Na and Cl that are found in supplements such as L1 and M9, which are used to grow the genetically engineered microorganism that will hyper-express fatty acids and fatty alcohols involved in the regeneration of the membrane. The overall TOC reduction achieved in the product ranges between 88.5 % and 96.4 % and the final TDS is below 0.5 ppm.

Acknowledgments

We would like to give special thanks to our colleagues Kevin Howard for their support in operating the system, and to Jeanie Howard for her support with the analysis of the samples.

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